Risk analysis of existing building heritage through damage assessment after L'Aquila earthquake 2009

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Keywords: damage assessment, fragility curves, ground motions, seismic risk, expected annualized loss

ABSTRACT

After recent seismic events, many information are made available about the seismic vulnerability of existing buildings. In particular, the data collected through the AeDES forms by the Italian Civil Protection provided information about recorded damages on thousands of buildings, with different structural typologies, construction materials and geometric properties. At the same time, the large extension of Italian accelerometric network allows us to estimate as well the recorded ground motions intensity measures with moderate approximation. In this work, a preliminary elaboration of the data available for the L'Aquila earthquake (2009) is presented, in order to provide fragility curves of the expected seismic damage and the loss curve estimating the reconstruction cost percentage. The data examined are available on Da.D.O. web-gis database and the preliminary results discussed in this paper regards the typology of old ordinary masonry buildings.

1 INTRODUCTION

Nowadays there is an increasing interest in the scientist community of developing tool for simulating damages scenarios useful in preventing and managing natural disaster, such as seismic events. Among these, simplified tools derived from a statistical observation of the damages suffered by structures during the last seismic events are, without any doubt, useful and practical to be used for seismic risk analysis at a large scale.

Recently, many studies have been published in literature for predicting the damage scenarios of the Italian buildings stocks. For example, among the others in (Rota et al. 2008) and in (Del Gaudio et al. 2016) study for deriving typological fragility curves are performed. While, in (De Risi et al. 2019) the estimation of the repair costs due to the L'Aquila earthquake is presented.

In this paper some preliminary results about a comprehensive risk analysis conducted by statistically examining the seismic damage data collected within the web-gis database Da.D.O. (Dolce et al. 2017, DPC 2015) are illustrated. In particular, the data elaboration is still in progress and the results here discussed regard the ordinary buildings in masonry. In a companion paper (Laguardia et al., 2019), a data elaboration regarding the reinforced concrete buildings for detecting if the application of the seismic isolation strategy is possible is presented.

Starting from a statistical observation of the damage occurred during the L'Aquila earthquake (2006), vulnerability and fragility curves are derived with numerical regressions for predicting different damage scenarios. The paper concludes showing a loss curve referred to the L'Aquila site and the related Expected Annualized Loss (*EAL*).

2 DA.D.O DATABASE AND DATA ELABORATION

The web-gis database Da.D.O. (Observed Damage database, Dolce et al. 2017, DPC 2015) collects the data of the observed damage of ordinary buildings after the principal Italian seismic events (Friuli 1976, Irpinia 1980, Abruzzo 1984, Umbria-Marche 1997, Pollino 1998, Molise e Puglia 2002, Emilia 2003, L'Aquila 2009, Emilia 2012). In addition to the observed damage data, other information may be found in this database, such as the buildings structural properties, their location within the Italian territory and some information about the characteristics of the main shock of the considered earthquake, such as: Moment Magnitude (M_W), location and depth of the seismic shocks epicentre, macro-seismic intensity for each municipality and for each location. As for buildings properties, one may found typological and general structural information about each investigated building, and observed damage expressed through the EMS98 classification (Grunthal 1998), varying from *D0* (null damage) to *D5*, the latter corresponding to the collapse. Such information were collected from the AeDES forms (Baggio et al. 2009) compiled during the technical surveys performed after seismic events in order to check the usability of the buildings, whose contents are fully available in the database. It is worth to note that within the AeDES form the damage level is grouped for simplicity in *D1* (slight damage), *D2-D3* (moderate-substantial damage), and *D4-D5* (very heavy damage-destruction).

In this study only the data referred to the L'Aquila earthquake (2009) are considered. For this seismic event, the surveys data of 74049 buildings are reported in 8 different sections within the database, which are:

1. Building identification;
2. Building description;
3. Typology;
4. Damage to structural elements and emergency interventions performed;
5. Damage to non-structural elements and emergency interventions performed;
6. External damage due to other constructions, networks, slopes and emergency interventions performed;
7. Foundation and ground conditions;
8. Usability judgment.

With these information, it is possible to evaluate the composition of the investigated building heritage, the most recurrent typology characteristics and the observed damage for each structural component (vertical structures, floors, stairs, roofs, partitions, pre-existing damage).

Once all the data were downloaded from the Da.D.O. web-gis platform (DPC, 2015), some statistical elaboration were performed, in order to analyse the information collected. In particular, all the evaluations illustrated in this study were obtained with a series of Matlab Routines (MathWorks Inc. 2017) where, depending on the case, also some selection filters were applied.

For example, in Figure 1 it is shown the percentage breakdown of the buildings typology calculated on the whole sample of 74049 buildings. As results, building having masonry structures are the most recurrent ones (79% of recurrence), while Reinforced Concrete (R.C.) frame structures result present with a percentage of 19%. Only the 2% of the building sample consists of R.C. wall structures (1%) and of steel frame structure (1%).

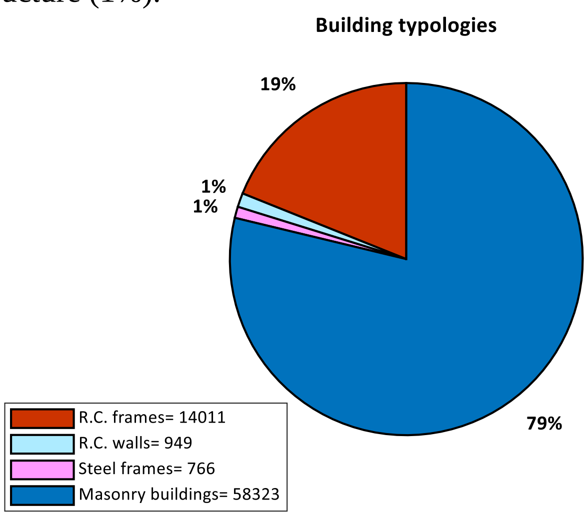

Figure 1. Percentage breakdown of building typologies within the Da.D.O. database.

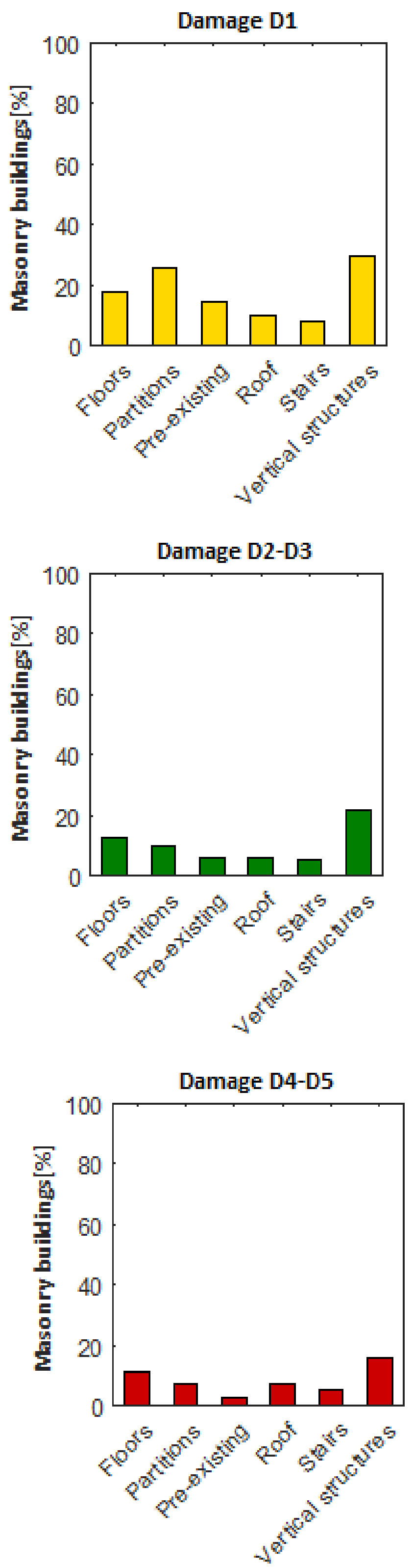

Figure 2. Damage distribution among different structural elements for masonry buildings by considering different damage levels.

Paying attention in this study to the masonry structures that are, as shown, prevailing in this case, in Figure 2 the observed damage distribution among the different structural elements is illustrated. It can be noticed that, the vertical elements results always the most damaged for all damage level considered, followed by partitions and floor elements.

2.1 *Seismic vulnerability assessment*

In order to perform a seismic vulnerability assessment starting from the observed damage, the first step is of associating an unique damage level to each surveyed building, starting from the recorded damages for each structural element. To this end, two different approaches may be followed. One approach consists of calculating the global damage as weighted average of all structural components damage, such as in (Di Pasquale and Goretti 2001), (Lagomarsino et al. 2015). While, with the second approach the global damage is defined as the maximum damage recorded among the structural components (Rota et al. 2008, Del Gaudio et al. 2016).

In Figure 3 it is shown the number of masonry buildings for each global damage level considered, by assuming the global damage as the maximum damage recorded among the structural elements. In doing so, only the damage of vertical structures, floors, and roofs are considered (Rota et al. 2008). In the Figure 3, the number of buildings for each damage class is represented through a histogram, while the cumulative percentage on the whole sample is represented through a continuous line. It can be noticed that in about the 60% of buildings a damage *D0* or *D1* was registered, while in 30% of buildings resulted a *D2* or *D3* damage, and only the 10% of buildings suffered a damage level *D4* or *D5*. The choice of considering the maximum damage stems from the fact the usually from the maximum observed damage depends the structure usability of and the related repair costs. Clearly, in this way the global damage results overestimated, since the maximum local one observed on single elements is extended to all the structure.

3 GROUND MOTION DATABASE

The Ground motion (GM) of L'Aquila earthquake was recorded by a wide number of accelerometric stations located throughout the Italian national territory. In this work, 62 of these stations are considered. These accelerometric stations belong to the Italian accelerometric network (RAN), managed by Italian Civil Protection Department (DPC), and to the Italian Seismic Network (RSN), managed by Italian Geophysics and Vulcanology Institute (INGV). Precisely. The GMs records of the stations adopted herein are taken from the Engineering Strong-Motion database (ESM database, Luzi et al. 2016). As known, the GMs of ESM are recorded according to two arbitrary axes, positioned along the east-west and north-south directions. In this work the records have been rotated along their principal axes by using the procedure proposed in (Razaeian and Der Kiureghian 2010) in order to avoid correlation between the two horizontal records. By using the so-derived GMs, the attenuation law of different Intensity Measures (IMs) may be obtained for the seismic event of L'Aquila 2009. The correlation of several IMs with structural response is widely discussed within the literature, such as in (Barazza et al. 2009, Morelli et al. 2018). In this study only the Peak Ground Acceleration (PGA) is taken into consideration, by adopting the following expression for the attenuation law:

$$\log(PGA) = Mw * a_1 - b_1 * \log\left(\sqrt{R_{epi} + h^2}\right) \quad (1)$$

where M_w is the moment magnitude of the L'Aquila earthquake assumed equal to 6.1, R_{epi} is the epicentral distance in km, h is assumed equal to 8.3 km, and a_i, b_i are the coefficients obtained through a non-linear regression derived from the PGA measured by the accelerometric stations. In Figure 4 the registered PGAs from GMs by varying the epicentral distance, and the attenuation law obtained with the regression are shown. In this case, a_i results equal to 0.4328and b_i equal to 1.5998, with a correlation factor R^2 of 0.91. For completeness, in the Figure 4 with dashed lines are also reported the curves individuating a 95% confidence interval.

4 VULNERABILITY ANALYSIS

The vulnerability assessment of the existing building heritage is performed by correlating the information on the observed damage and the intensity measures recorded or estimated at each site. The vulnerability curves are obtained by regression by using a logarithmic expression:

$$D = a + b \cdot log(IM) \quad (2)$$

where D is the observed damage expressed in the EMS-98 scale, IM is the intensity measure corresponding to the PGA evaluated with the attenuation law proposed in the Eq. (1), and a and b are the coefficients obtained by a least square regression.

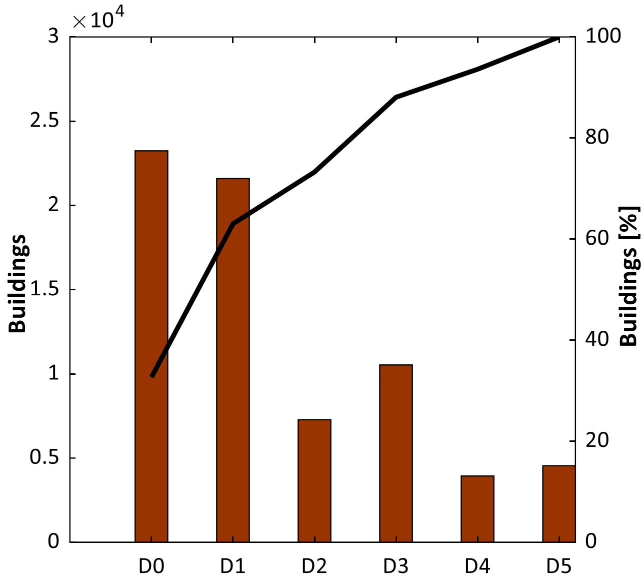

Figure 3. Global damage assessment performed by using the approach proposed by (Rota et al. 2008).

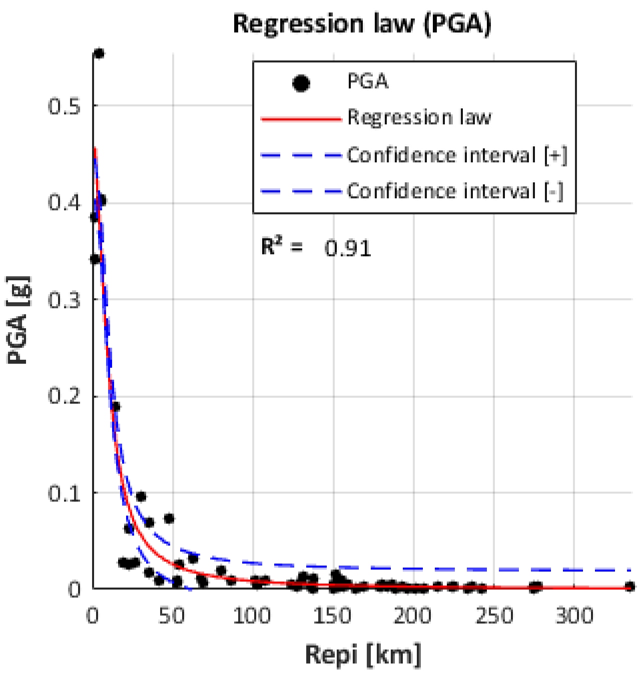

Figure 4. Attenuation law obtained by Regression for the Peak Ground acceleration.

The average damage on the buildings is determined by subdividing the sample into 20 intervals with uniform PGA. Within each *k-th* subsample, the weighted average $\mu_{d,k}$ of the observed global damage is evaluated through the following expression:

$$\mu_{d,k} = \frac{\sum_{i=1}^{n} D_{k,i}}{\text{n}} \qquad (\text{k}=1,\ldots,20) \quad (3)$$

where $D_{k,i}$ is the global damage level for the i-th building within the *k-th* subsample, and *n* is the total number of buildings into the considered subsample.

As preliminary result, in Figure 5 it is reported the correlation between the observed damage for masonry building of type A (poor masonry, without chains) in according to the Da.D.O. vulnerability class classification, and Peak Ground acceleration (PGA). It can be noticed that with a non-linear regression the correlation between damage and the PGA is quite good (R^2=0.73). In this case, it is found that the coefficient of the Eq. (2) result equal to: a=3.30 and b=0.79.

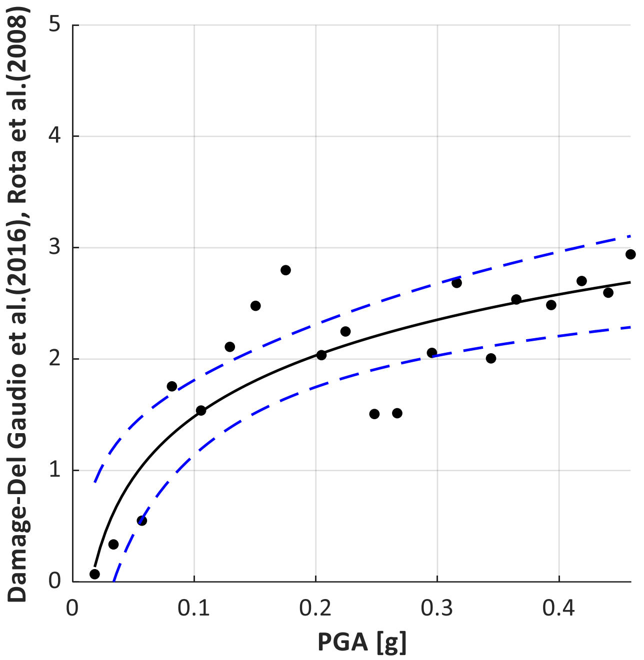

Figure 5. Vulnerability curve for the masonry buildings of vulnerability class A.

Furthermore, the vulnerability curves confirm that this building typology has a very high vulnerability with an observed damage higher than 2 for PGA>0.2g. For sake of completeness, in Figure 6 all the vulnerability classes considered within Da.D.O. are considered, namely from *Class A* (the worst) previously reported in the Figure 5, to the *Class C1* (the best class). It can be noticed that the correlation is quite good in almost all the cases and, as expectable, by considering masonry building with higher quality (i.e. *class C1*) the vulnerability is sensibly reduced. For each regression, the 95% confidence interval is reported (dashed curves), too. Finally, in the Table 1 the coefficient of *a* and *b* of the vulnerability curves (Eq. 2) are reported, together with the correlation factor R^2, the mean squared error (*MSE*) and the number of building belonging to each vulnerability class considered. It is worth to remark that the global damage here discussed is associated to the maximum damage recorded among the structural components in according to (Rota et al. 2008) and (Del Gaudio et al. 2016) works.

Table 1. Coefficients of the vulnerability curves (Eq. 2).

Vuln. Class	*a*	*b*	*R2*	*MSE*	*N build*
A	3.30	0.79	0.73	0.218	43833
B	2.11	0.48	0.59	0.164	30944
C1	0.87	0.21	0.77	0.013	27057

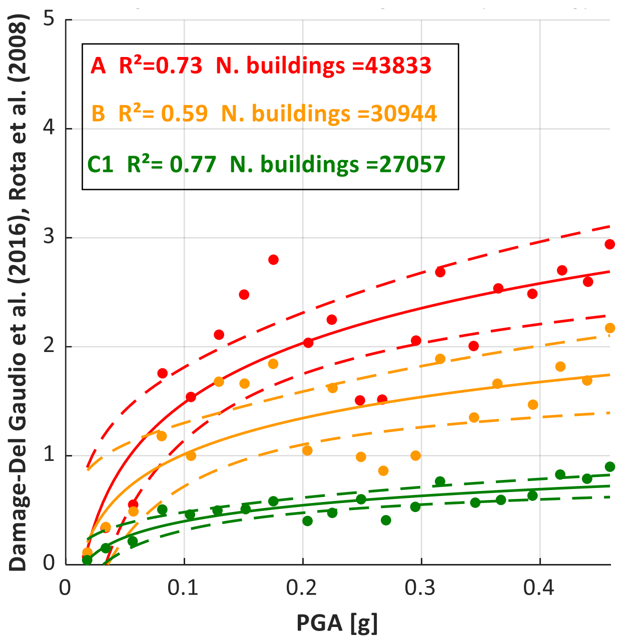

Figure 6. Comparison among the vulnerability curves of different masonry vulnerability classes.

5 FRAGILITY CURVES

The fragility curves allow to assess the probability of exceeding a given global damage state as a function of an *IM* representing the ground motion:

$$P[D \geq d|IM] \quad (4)$$

In particular, in this study the fragility curves are calculated by considering the probability of exceedance of the 5 damage states (*D0-D5*) in function of the PGA. By considering the maximum likelihood principle, the mean (μ) and the square deviation (σ) of the sample are used to define a log-normal cumulative distribution (Rota et al. 2008):

$$p = F(D|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{IM_{Lim}} \frac{e^{-\frac{[ln(IM)-\mu]^2}{2\sigma^2}}}{IM} dIM \quad (5)$$

In Figure 7 it is shown the fragility curve for the masonry building of *Class A*. As it can be seen, even for moderate level of PGA (i.e. PGA<0.1g) the probability to observe damage is quite high. Specifically, the probability to exceed damage *D1* is about 0.42 and the probability to exceed *D3* is about 0.2. Therefore, this confirms the very high vulnerability of these buildings type. These results are in good agreement with other available within the literature, such as (Del Gaudio et al. 2016).

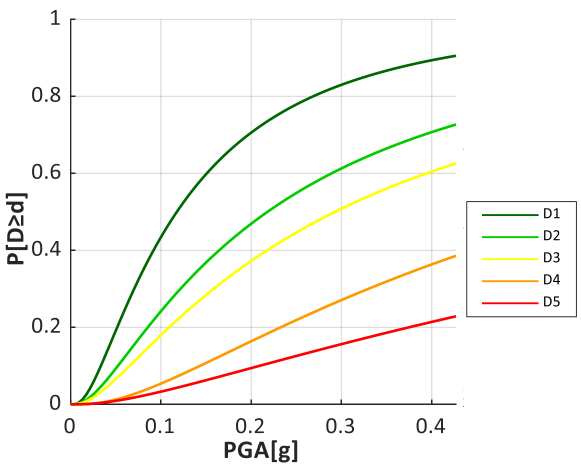

Figure 7. Fragility curves for the masonry buildings of class A.

6 EXPECTED ANNUAL LOSSES CURVES

In this paragraph it is shown a simplified loss curve assessment related to vulnerability *Class A* of masonry buildings. The curve is built by associating the frequency of occurrence of the PGA for the L'Aquila site, by using the hazard curve provided by INGV (2007) with the expected losses derived from the observed damage, i.e. by using the consequence correlation proposed within the ATC-13 (1985). It associates the buildings observed damage to the Reconstruction Costs (RC), as shown in Table 2. More in detail, the whole building sample has been subdivided into 20 subsamples with uniform and progressive frequency of occurrence, while the average damage score has been assessed within each subsample as done for the vulnerability curves.

Table 2. ATC-13. Reconstruction cost ratios by varying the damage state.

Damage state	**RC Range (%)**	**Central RC (%)**
1 - None	0	0
2 - Slight	0-1	1
3 - Light	1-10	5
4 - Moderate	10-30	20
5 - Heavy	30-60	45
6 - Major	60-100	80
7 - Collapse	100	100

The correlation between the Reconstruction Costs percentage and the annual frequency of occurrence λ for L'Aquila site is reported in Figure 8. In this Figure it is also reported the loss curve obtained by a numerical regression through the following hyperbolic expression:

$$RC = a + \frac{b}{\lambda^c} \quad (\%) \quad (6)$$

where *RC* is the reconstruction cost expressed in percentage of the total value of the building, *a* and *b* are the parameters obtained through regression and λ is the annual frequency of occurrence. In this case a=-667.33, b=641.91, c=0.020426, with a R^2=0.57. The Figure 8 also reports the annual frequency related to a return period of V_R of 30, 50, 475 and 975 years. They correspond to the four limit states considered by the NTC-18 (2018), having a PVR of 81%, 63%, 10% and 5%, with a nominal life V_N equal to 50 years and a coefficient of use C_u=1.0.

The Expected Annualized Loss (*EAL*) (ASTM 1999), measuring the average yearly amount of loss when one accounts for the frequency and severity of various levels of loss is given by the area enclosed by the curve (Porter et al. 2004). In this case it results equal to 1.89 % by considering the maximum damage recorded among the structural components (Rota et al. 2008, Del

Gaudio et al. 2016). Therefore, in this sense the value so-calculated overestimates the actual one.

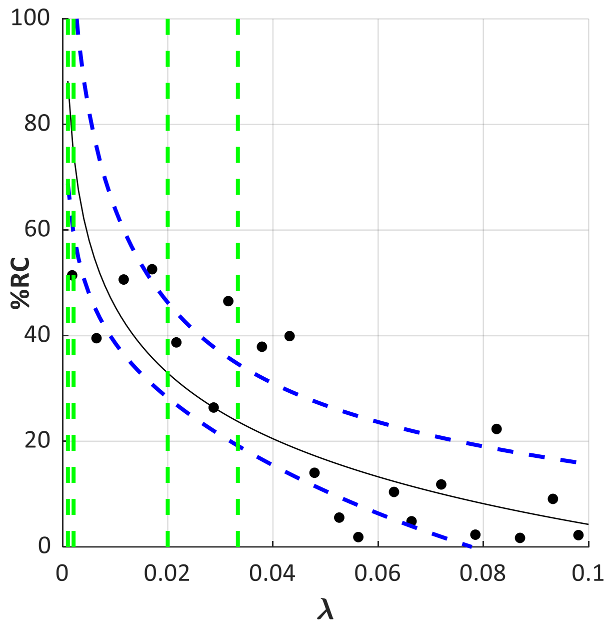

Figure 8. Loss curve for the masonry buildings of vulnerability class A.

7 CONCLUSIONS

Tools for simulating damages scenarios are very useful in preventing and managing seismic events. To this end, in this paper the data available within the web-gis database Da.D.O. are processed. In particular, the elaboration of these data is still in progress and in the present study only the preliminary results related to masonry structures belonging to the vulnerability class A have been taken into account by considering the seismic event of L'Aquila. In totally, the survey data reported for more than 43000 ordinary masonry buildings have been considered in this preliminary study.

Vulnerability and fragility curves have been derived with numerical regressions, starting from the observed correlations between the global damage observed and the PGA, chosen in this study as seismic intensity measure (IM). Finally, a typological loss curve has been also proposed by referred to the L'Aquila site, for predicting the expected loss depending on the annual occurrence frequency of a certain seismic event.

The methodology proposed may be extended to the other vulnerability classes in order to obtain EAL previsions to be used within management programs aimed to the evaluation and reduction of the seismic risk. The main advantage of this observational approach is represented from the fact that the derived prediction tools are capable of simulating damage scenarios for a very large sample of buildings, although they may differ each other for construction details.

Finally, the entire Da.D.O. database is currently examined and the obtained results will be shown in future.

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